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Conventional Water Treatment and Direct Filtration: Treatment and Removal of Total Organic Carbon and Trihalomethane Precursors

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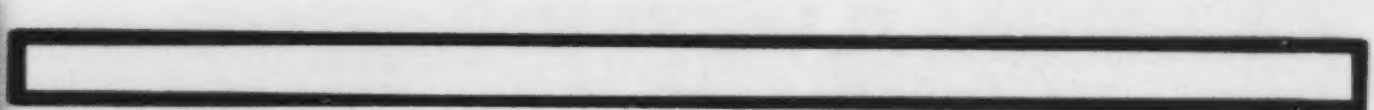

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16. ABSTRACT

What can be accomplished by conventional water treatment plants and direct filtration plants to remove organic matter and trihalomethane (THM) precursors? After describing the fundamentals of coagulation of humic substances for alum and cationic polyelectrolytes, field studies of two conventional-type water treatment plants are discussed. THM formation through the plants is examined, and removals of total organic carbon (TOC) and THM are summarized. Variables such as plant operation, water quality, and plant design that affect THM formation control and precursor removal are reviewed. Direct filtration is then examined as a treatment scheme in terms of traditional measures of performance and in terms of performance for removals ot TOC and THM precursors. Conventional-type water treatment facilities are shown to be effective in removing TOC and THM precursors and in controlling THM formation. Both plants effectively controlled THM formation because of the effectiveness of the coagulation process, pH conditions during treatment, and their chlorination practice. Direct filtration with cationic polymers as the sole coagulant is a feasible treatment process for waters of low to moderate TOC and total trihalomethane levels.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

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CHAPTER 8

Conventional Water Treatment and Direct Filtration: Treatment and Removal of Total Organic Carbon and Trihalomethane Precursors

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James K. Edzwald

Department of Civil Engineering
University of Massachusetts
Amherst, Massachusetts

8.1 INTRODUCTION

Conventional water treatment plants are used to remove suspended and colloidal particles from water supplies. These plants employ a series of processes consisting of coagulation-flocculation, sedimentation, and filtration as shown in Figure 8.1*a*. A variety of coagulants and coagulant aids are used. Alum is the most common primary coagulant, and organic polymers are frequently used as coagulant aids. Their function is to destabilize particles and produce large aggregates or flocs that settle readily. An objective then in a conventional water plant is to remove most suspended solids by sedimentation leaving filtration as a polishing step. Direct filtration, on the other hand, is a treatment scheme whereby all of the particulate solids must be removed in the filters; there is no sedimentation step as shown in Figure 8.1*b*. Direct filtration may include a flocculation tank or the water may bypass flocculation and go directly to the filters. The latter scheme is called in-line filtration. In either case it is necessary to add coagulants before filtration to destabilize the particles in the raw water. Primary coagulants used include alum, iron salts, and cationic polyelectrolytes.

Conventional plants are used to treat both turbid waters and waters containing natural color (humic substances). For the latter case, alum is most often used as the coagulant. Direct filtration plants in North America

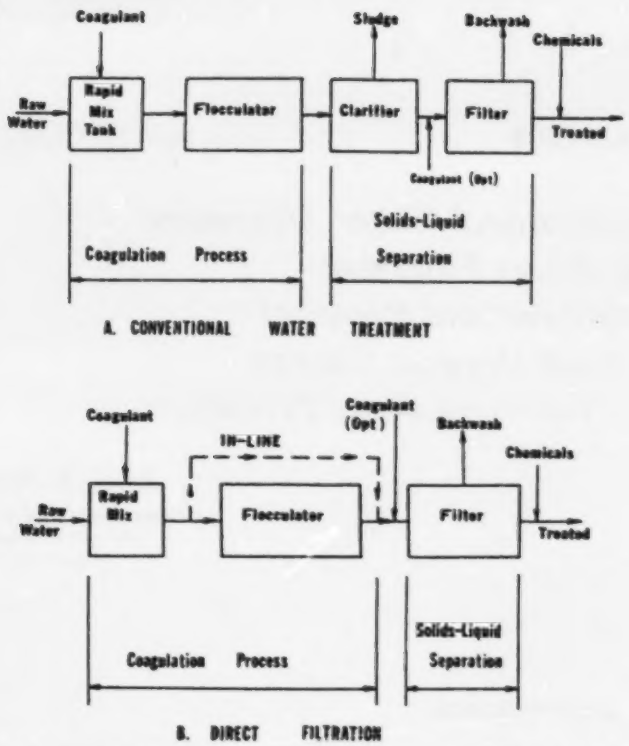

Figure 8.1. Schematic diagrams of conventional water treatment plant (*a*) and direct filtration plant (*b*).

have been designed primarily on the basis of turbidity removal with best application to low-turbidity raw waters. It was discovered in the 1970s that trihalomethanes (THMs) are produced within water treatment plants as by-products of chlorination (1,2,3). A variety of organic compounds present in natural waters can react with chlorine to form volatile chlorinated by-products (mostly, the THMs) and nonvolatile chlorinated by-products [frequently measured as a group parameter, as nonpurgeable organic halide (NPOX)]. Humic substances that cause natural color are both the largest fraction of organic matter and THM precursors in most natural waters. The Environmental Protection Agency (EPA) in 1979 amended the National Interim Primary Drinking Water Regulations (4) and established a maximum contaminant level (MCL) of 0.10 mg/L for total trihalomethanes (TTHMs). Water treatment plants must now be concerned about control of THMs and organic matter as well as the traditional parameters of color and turbidity.

There are several ways to control THM formation and to remove THM precursors. EPA (5) has identified several methods as "Best Generally Available." One of these is improved clarification for reduction of THM precursors. Improved clarification means improved coagulation and applies to both conventional and direct filtration plants. The major goal of this chapter is to describe what can be accomplished by conventional water treatment plants and direct filtration plants in removing organic matter and THM precursors. To accomplish this goal the chapter is divided as follows. First, fundamentals of coagulation of humic substances are described for two different coagulants, alum and cationic polyelectrolytes. Second, the results of field studies of two conventional-type water treatment plants are described and discussed. THM formation through the plants is examined and removals of TOC and THM precursors are summarized. To insure general application of the results, the discussion focuses on important water quality, plant operating, and plant design variables that affect THM formation control and THM precursor removal. Finally, direct filtration is examined as a treatment scheme in terms of traditional measures of performance (filtered water turbidity and color, and head loss development) and in terms of performance for removals of TOC and THM precursors.

8.2 COAGULATION OF HUMIC SUBSTANCES

8.2.1 Background

Prior to the early 1970s and the discovery of THMs in drinking water, the primary interest in the coagulation and removal of humic substances was for the removal of natural color. Research by Black and co-workers (6,7), Hall and Packham (8), and Mangravite et al. (9) demonstrated the importance of pH and coagulation stoichiometry. An optimum pH range of 5 to 6 was cited for alum coagulation of humic substances. Optimum pH means those pH conditions at which the largest color reduction can be achieved with the lowest alum dosage. Their research also showed a stoichiometric dependence between the initial concentration of humic matter (color) and the alum dosage needed for good coagulation.

Since the discovery of THMs, research interests in the coagulation of humic substances shifted from color reduction to the removals of total organic carbon (TOC) and THM precursors (e.g., 10–15). More recently, coagulation studies have examined the removals of nonvolatile chlorinated precursors (16,17). These studies have verified the older work on color removal regarding optimum pH conditions and the stoichiometric alum coagulant requirements.

In practice, a wide range in removal efficiencies for TOC and THM precursors have been reported (see Ref. 18). Some of the variation is due to differences in the ability of coagulants to remove a variety of precursors

from various waters. However, some of the variation in removals is due to differences in coagulants tested—alum versus cationic polymers. Other important factors explaining variation in the reported removals are differences in the nature of the THM precursors, in treatment conditions, and in the experimental protocol. Data have been reported for humic acids, fulvic acids, and uncharacterized organic matter from real waters. The pH of coagulation and the experimental protocol for measuring THM precursors varies widely, especially where field data are reported. THM precursors are measured indirectly by measuring the total trihalomethane formation potential (TTHMFP). Experimental methods for TTHMFP measurements have not been standardized. Different investigators may use different pH, temperature, or formation period conditions. All of the above contribute to discrepancies in reported data on the efficiences of coagulation for removals of TOC and THM precursors.

The goal of Section 8.2 is to present principles on the removal of humic substances by coagulation for alum and cationic polyelectrolytes. The removals of TOC and TTHMFPs for waters containing naturally occurring organic matter, particularly humic substances, are reported for well-controlled coagulation experiments. First, the procedures for properly evaluating the effectiveness of coagulants via jar tests (bench-scale batch studies) are explained. Next alum coagulation is explained. Finally, cationic polyelectrolytes are examined as sole coagulants. The material in this section serves as a foundation for subsequent sections.

8.2.2 Jar Test Procedures

Jar tests are bench-scale batch experiments used by environmental engineers and water plant operators. They are used to evaluate the destabilizing ability of various coagulants, to choose coagulant dosages, and to evaluate coagulant aids. The jar test data are commonly judged in terms of the ability of the coagulant to produce a low residual turbidity following coagulation (rapid mix), flocculation (slow mix), and sedimentation. To evaluate coagulation for THM precursor removal, the traditional turbidity and color measurements are not adequate. Jar test experiments must include additional measurements.

THM precursor removal by coagulation can be determined by measuring the difference between the TTHMFPs of the raw and treated waters. Herein TTHMFP measurements are based on 7-day formation periods at pH 7.5 and 20°C. It is critical that sufficient chlorine be added to the samples in the TTHMFP test so that a free chlorine residual exists for the entire 7-day formation period. A rule of thumb is an initial dose based on 3–5 mg Cl_2 per milligram of TOC is usually adequate. Standardizing the pH of the TTHMFP test is also critical to separate the influence of pH on coagulation from pH effects on THM formation.

pH is an important variable in coagulation experiments that must be

controlled, especially when using hydrolyzing metal coagulants such as alum. pH affects the chemistry of aluminum and the stability of colloids and organic matter present in the raw water. The proper way to control pH in jar test experiments is described below.

The pH of the raw water is first adjusted to the desired study value with strong acid (HCl) or base (NaOH). Alum is then added, but with the simultaneous equivalent addition of $NaHCO_3$ to neutralize the acidity of the alum, and thus maintain a constant pH in the critical rapid mixing stage of coagulation. This method has been used successfully in the author's laboratory. In coagulation experiments examining a range of pH conditions from 5.5 to 7.5, measured pH values at the conclusion of the jar tests (after the settling period) are usually within 0.2 pH units of the initial pH. Addition of alum to the samples followed by adjustment of pH to a target study value is not a good procedure because the kinetics of aluminum reactions with water and organic matter are so rapid that these reactions will have taken place prior to pH adjustment.

In summary, pH must be controlled in coagulation experiments and standardized for all TTHMFP measurements. TTHMFP measurements are, however, time consuming. It may be a week or more before the THM data are available to evaluate the effectiveness of coagulation. TOC measurements may be used as a nonspecific indicator of the effectiveness of coagulation for removal of organic matter. However, this test also takes time and requires specialized, expensive equipment. A good surrogate parameter for TOC and THM precursors (TTHMFPs) is UV (254 nm) absorbance. It is especially good in jar test studies because, like turbidity, it can be measured easily, rapidly, and inexpensively. Measurements on filtered (glass fiber filters, Whatman 934-AH) and unfiltered samples at a fixed pH are recommended (e.g., pH 7.5). In this chapter unfiltered measurements are referred to as total UV (TOTL-UV) and filtered measurements are referred to as soluble UV (SOL-UV). The usefulness of UV is demonstrated in the material that follows.

8.2.3 Alum Coagulation

Table 8.1 compares the main features of the coagulation of humic substances with alum. It is used to guide us through this subject in which data are presented to illustrate pH effects, stoichiometric considerations, and removals of TOC and THM precursors.

8.2.3.1 pH

The literature indicates that optimum pH conditions exist between pH 5 to 6. Figure 8.2 compares coagulation at pH 5.5 with pH 7.2 for Grasse River water, a highly colored water supply of low alkalinity and turbidity. A detailed description of this supply is provided in Section 8.3.1. The data clearly

TABLE 8.1
Comparison of Alum Coagulation of Humic Substances at Different pH Conditions

	pH 5–6	pH 6–8.5
Literature	Optimum	Not optimum
Stoichiometry	Coagulant dosage increases with increasing humic concentration	Coagulant dosage increases with increasing humic concentration
Flocculation kinetics	Could be limiting due to dilute humic concentrations	Should be more rapid due to precipitation of $Al(OH)_3(s)$ particles
Mechanism	(1) Low TOC: precipitation of aluminum humates (2) High TOC: adsorption of humic substances on aluminum hydroxide particles	Adsorption of humic substances on aluminum hydroxide particles

demonstrate that lower alum dosages are needed at pH 5.5 than at the higher pH for good coagulation. Optimum pH conditions of 5–6 not only apply to the coagulation of TOC and THM precursors, but also organic halide precursors (measured as TOXFP). Reckhow and Singer (17) have reported on the coagulation of fulvic acid showing optimum pH conditions of 5 to 6 for removals of TOXFP. Consequently, optimum pH conditions for coagulation applies to the total pool of organic matter (TOC), to that fraction of the organics that produces volatile chlorinated organics (THMs), and to that fraction that produces nonvolatile chlorinated organics (NPOX).

Figure 8.2 shows that no restabilization of floc particles occurs at pH 7.2. Furthermore, alum doses above that first needed for good coagulation produces only a small increase in the removals of NPTOC and TTHMFP. There is evidence at pH 5.5 of slight restabilization of flocs at aluminum dosages of 4–6.5 mg/L (alum dosages of 50–75 mg/L). The residual turbidity and unfiltered UV data show poorer settling of the floc in that alum dosage region, followed by good coagulation and settling at higher aluminum doses.

The data also show that UV (254 nm) absorbance is a good surrogate parameter for evaluating removals of NPTOC and TTHMFP in jar test experiments. Data collected in the author's laboratory have demonstrated excellent correlations between UV and both NPTOC and TTHMFP (19,20). Its use in practice is addressed in Sections 8.3 and 8.4.

8.2.3.2 Stoichiometry

Figure 8.3 presents coagulation data at pH 5.5 for two different systems—the Grasse River and a synthetic water containing fulvic acid (Contech)—at

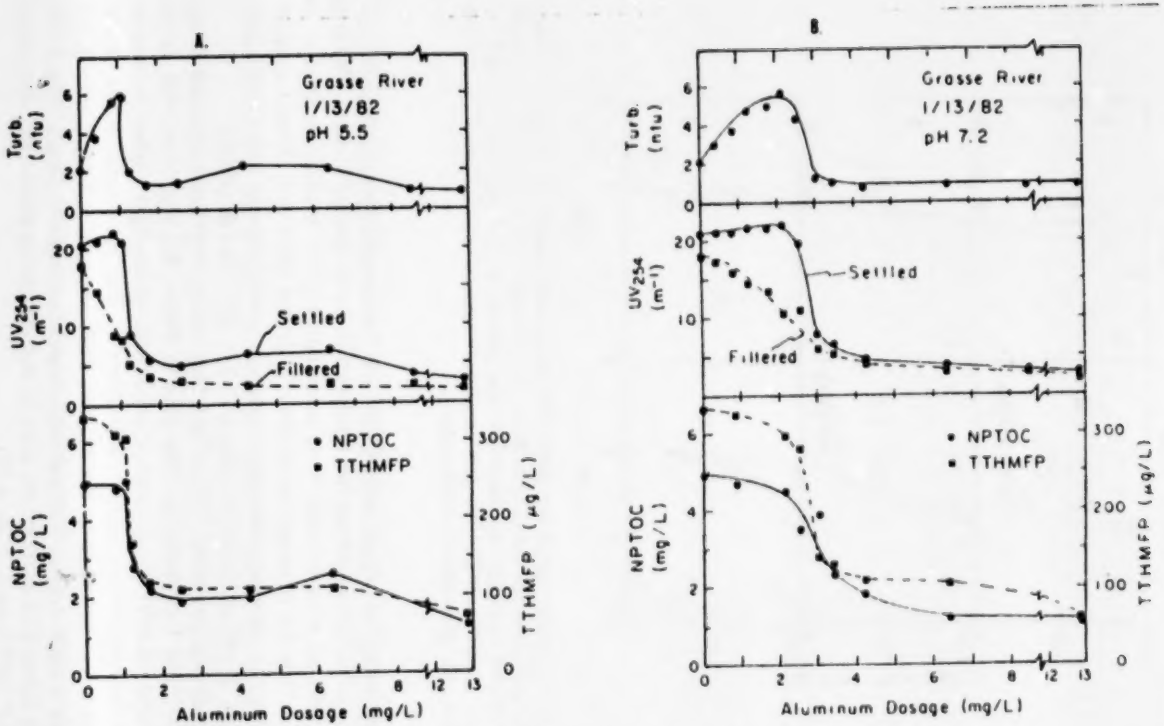

Figure 8.2. Jar test results using alum for pH 5.5 (*a*) and pH 7.2 (*b*). Raw water quality: 2.1 ntu turbidity, 20.9 m^{-1} (0.209 cm^{-1}) UV (254 nm), 4.9 mg/L NPTOC, and 332 µg/L TTHMFP. 1 mg/L Al equals 11 mg/L $Al_2(SO_4)_3 \cdot 14\ H_2O$.

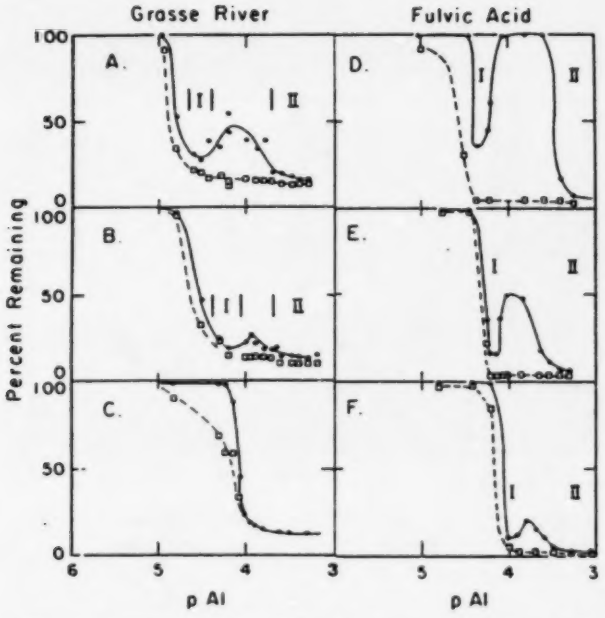

Figure 8.3. Organic matter remaining following alum coagulation at pH 5.5. Initial NPTOC conditions for the Grasse River: (*a*) 2.1 mg/L; (*b*) 4.5 mg/L; (*c*) 6.5 mg/L. Initial NPTOC conditions for the fulvic acid system: (*d*) 2.5 mg/L; (*e*) 3.4 mg/L; (*f*) 4.9 mg/L. (*Solid lines*) UV (254 nm) on settled samples; (*dashed lines*) UV (254 nm) on settled plus glass fiber filtered samples.

different initial concentrations of TOC. At the lowest concentrations of TOC (Fig. 8.3, *a* and *d*), there are two coagulation zones labeled I and II. The area of restabilization separating these coagulation zones is characterized as an area in which the particles are stable and do not settle well. Zone I coagulation occurs at relatively low total aluminum concentrations (Al_T), while Zone II occurs at pAl of about 3.5 (Al_T of 3.2×10^{-4} *M*) or greater.

Increasing the initial TOC of the two waters requires additional aluminum for Zone I coagulation. The data in Figure 8.3 also show that as the concentration of TOC increases, Zone I shifts to the right (higher Al requirements) and apparently merges with Zone II. For the Grasse River, no restabilization is observed at the highest TOC water of 6.5 mg/L (Fig. 8.3*c*), and only a small degree of restabilization is observed at 4.5mg/L (Fig. 8.3*b*). For the fulvic acid system, the area of restabilization essentially disappears at a TOC of 4.9 mg/L (Fig. 8.3*f*).

The data show a stoichiometry between the alum dose and the raw water TOC concentration. This is measured by an Al_T/TOC ratio—the Al_T dose required for good coagulation divided by the raw water TOC. At pH 5.5 this

TABLE 8.2
Stoichiometric Ratios and Removals of TOC and TTHMFP[a]

System	pH 5.5			pH 7.2		
	Al/TOC (mg/mg)	Percent Removals		Al/TOC (mg/mg)	Percent Removals	
		NPTOC	TTHMFP		NPTOC	TTHMFP
Fulvic acid	0.5–0.6	70–85	65–85	0.9–1.6	70–80	75–80
Grasse River	0.4–0.6	50–70	60–80	0.9–1.3	50–70	60–75

ratio is about 0.5 for both raw water systems as shown by the data in Table 8.2. If coagulation is practiced at higher pH, there is also a stoichiometric dependence, but the Al_T/TOC ratio is higher. At pH 7.2 the ratio is about twice that at pH 5.5. The Al_T/TOC ratio is significant and practical. If the raw water TOC is known, it can be used to estimate alum dosages for humic-type waters. The TOC can be measured directly or estimated from TOC-UV correlations. The use of UV absorbance at 254 nm as a surrogate parameter for organic matter and THM precursors is discussed in Sections 8.3 and 8.4.

8.2.3.3 Coagulation Mechanisms

Two mechanisms are described and illustrated in Figure 8.4. They follow concepts of particle formation for aluminum in the presence of humic matter presented by Snodgrass et al. (21), and coagulation mechanisms for humic substances presented by Dempsey et al. (15). The coagulation mechanism for alum depends on the pH of coagulation, the Al_T dose, and the raw water concentration of humic matter represented by the TOC concentration.

At the optimum pH conditions of pH 5–6, coagulation can occur by two mechanisms depending on the TOC concentration. At low TOC concentration the required Al_T dose is relatively low, and coagulation is achieved by precipitation of aluminum-humate particles produced by the chemical interaction of positively charged aluminum hydrolysis species with negatively charged humic macromolecules (see Fig. 8.4). The humic matter precipitates out of solution when the negative charge is satisfied by an equivalent positive charge from the dissolved aluminum species. It is proposed that Zone I in Figure 8.3 is due to this mechanism. Using data in Figure 8.3 and Table 8.2, it is proposed that this mechanism is applicable when raw water TOC concentrations do not exceed 4–5 mg/L. The required Al_T dose would be 10^{-4} *M* or less (alum dose of 30 mg/L or less). If alum is added above the dosage required for precipitation of aluminum-humate, the aluminum-humate particles can adsorb positively charged soluble aluminum from solution, resulting in stable, positively charged aluminum-humate floc.

The second mechanism involves the precipitation of aluminum hydrox-

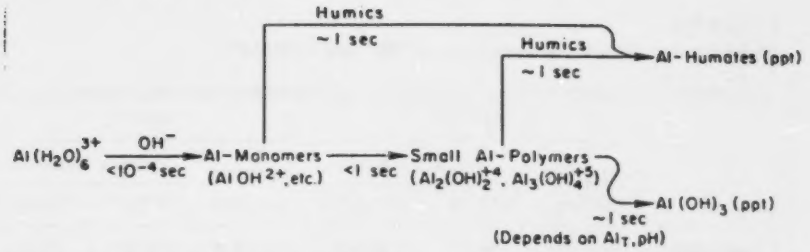

Figure 8.4. Proposed mechanisms for alum coagulation of humic substances. Pathways at top resulting in Al-humate precipitation favored by low TOC and pH < 6. Pathway resulting in $Al(OH)_3$ precipitation favored by high TOC or pH above approximately 6.

ide and the removal of organic matter by adsorption on aluminum hydroxide particles. This mechanism operates at pH 5.5 when high Al_T doses are needed due to high TOC concentrations (above 4–5 mg/L), or at higher pH (pH 6–8) conditions. At Al_T dosages of about 3.2×10^{-4} *M* or higher (alum of 100 mg/L or higher), aluminum hydroxide precipitation occurs. In Figure 8.3 this is shown as Zone II. For low TOC waters (less than 4–5 mg/L), it is shown as a second zone of coagulation at pH 5.5 following restabilization. For TOC concentrations greater than 4–5 mg/L, the Al_T doses are so high (about 3.2×10^{-4} *M* or higher) that aluminum hydroxide precipitation is favored kinetically over precipitation of aluminum humates (see Fig. 8.4). It is proposed then that removal of humic substances occurs by adsorption on aluminum hydroxide particles. The adsorption process may involve both soluble aluminum-humate complexes and uncomplexed humic matter.

8.2.3.4 Removals of NPTOC and THM Precursors

Table 8.2 summarizes the removals of NPTOC and TTHMFP achieved by alum coagulation with flocculation and settling periods. No filtration of the samples took place. Alum coagulation is effective in removing TOC and THM precursors at both pH conditions; however, coagulation at pH 5.5 requires lower alum dosages—about one-half the dosage needed at the higher pH condition. The data show that removals of 70% can be achieved for the Grasse River. In Section 8.3.4 the results of these laboratory experiments are compared with full-scale treatment plant data for the Grasse River.

For the Grasse River, the TOC concentration frequently exceeds 4 mg/L so that the mechanism of removal of dissolved organic matter is by adsorption on aluminum hydroxide. The lower alum dosage at pH 5–6 is consistent with the observations that adsorption of organic matter on aluminum oxides is pH dependent with maximum adsorption occurring at pH 5–6 (22).

8.2.4 Cationic Polyelectrolytes

Cationic polymers can coagulate humic substances (23–25). Below, jar test data are used to describe the coagulation model. Important features of the model are then outlined. The application of cationic polymers in direct filtration is presented in Section 8.4.

8.2.4.1 Coagulation Model

Figure 8.5 shows jar test data for a synthetic water containing 10 mg/L humic acid buffered at pH 6.3 with $NaHCO_3$. A high charge density, cationic polyelectrolyte (a quaternized polyamine) was used as the coagulant over a wide range of dosages.

In this jar test, electrophoretic mobility (EPM) measurements were also made and are shown at the bottom of the figure. At low dosages (0–6 mg/L), underdosing is observed whereby an insufficient amount of positively charged polymer has been added to achieve particle destabilization. This is

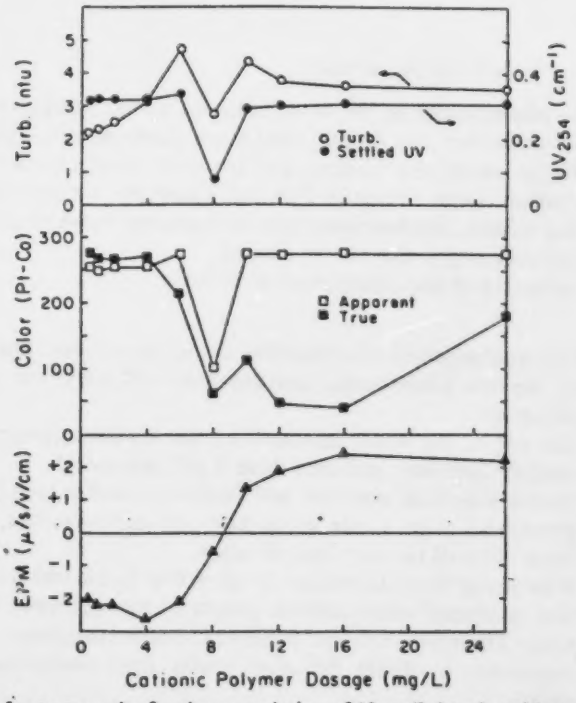

Figure 8.5. Jar test results for the coagulation of 10 mg/L humic acid at pH 6.3 using a cationic polymer.

reflected in the UV and color data as well as the negative EPM values. At a dosage of 8 mg/L, the jar test optimum for UV and color, the mobility is close to zero with a slight negative charge. At this point, enough cationic polymer has been added to neutralize the charge of the humic matter. Charge neutralization is important, but the mechanism is different from that traditionally described for cationic polymers adsorbing on colloidal solid surfaces. Aggregates (precipitates of humic matter and cationic polymer) are formed as a result of chemical cross-linking between the negatively charged humic macromolecules and the cationic polymers (23). Overdosing is observed at dosages greater than 8 mg/L. Here, the suspension of particles is restabilized as indicated by the increase in UV and apparent color. Charge reversal occurs with excess polymer addition as indicated by the postive EPM values.

The name given to this model is the Charge Neutralization/Precipitation model (26). Coagulation occurs at the point that the negatively charged humic macromolecules are neutralized by the addition of cationic polyelectrolyte causing precipitation of a cationic polymer-humic solid phase. The mechanism is analogous to the alum coagulation model for low TOC waters at pH 5–6.

8.2.4.2 Features of the Model

Polymer effectiveness in the coagulation of humic substances depends on polymer properties, the humic substances (concentration, chemical structure, charge, molecular weight), and the bulk water chemistry (pH, Ca^{2+} concentration, ionic strength). Polymer properties include charge density, molecular weight, and functional group chemistry; however, the single most important property is the charge density.

A summary of important features follows:

- Cationic polymers can coagulate humic substances. The dose depends on the raw water humic concentration and the charge density of the polymer.
- The pH of the water affects the total negative charge of the humic matter; therefore, polymer dose is pH dependent.
- Overdosing with polymer will produce a stable (positively charged) precipitate. This stable precipitate will not flocculate rapidly nor be removed well by deep bed filtration.
- Kinetics of flocculation can be slow due to the low floc volume fraction produced when cationic polymers form polymer-humic precipitates. Therefore, cationic polymers as sole coagulants would be more applicable in direct filtration rather than conventional treatment plants.

8.3 CONVENTIONAL WATER TREATMENT PLANT PERFORMANCE

8.3.1 Description of Water Supplies

Two representative water supplies were selected for study. Both supplies are treated by conventional-type water treatment plants that were evaluated for their ability to control THM formation and to remove TOC and THM precursors.

The Grasse River (Canton, New York) is a low alkalinity, highly colored supply typical of many water supplies found in many regions of the United States such as New York, New England, and the Pacific Northwest. The Glenmore Reservoir (Oneida, New York) is a protected upland water supply of low turbidity. The concentrations of organic matter and THM precursors in both raw water supplies undergo a well-defined seasonal variation (19,20). Figure 8.6 shows this for the Grasse River. Highest concentrations occur in the summer, particularly late in the summer, and lowest concentrations occur in the winter during river ice-cover. The observed seasonal variation is not unique. It occurs for other surface waters and should be recognized by water supply utilities, consulting engineering firms, and regulatory agencies

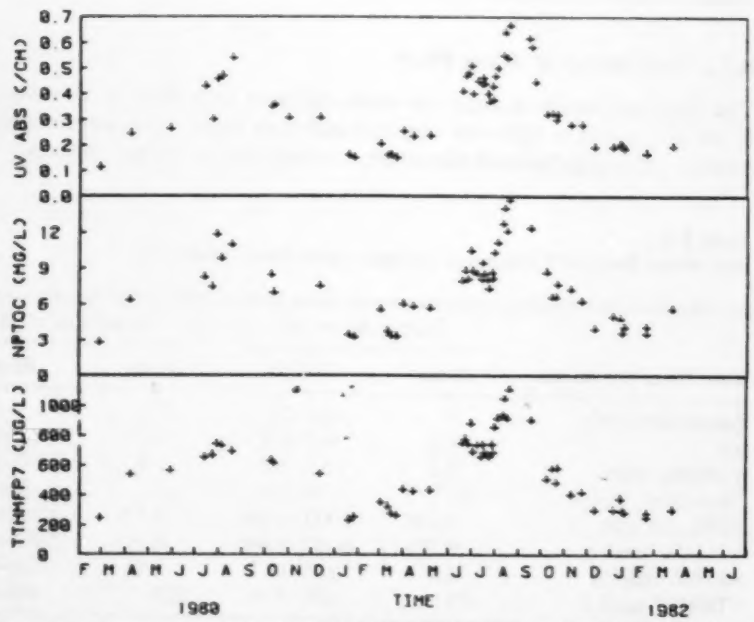

Figure 8.6. Seasonal variation in UV (254 nm), NPTOC, and TTHMFP (7-day, pH 7.5, 20°C) for the Grasse River.

concerned with pilot plant studies or full-scale water plant investigations. The poorest water quality with regard to the highest concentration of natural organic matter does not occur during autumn leaf fall or during spring runoff conditions, but in the summer. The higher water temperatures in the summer coupled with high raw water THM precursor concentrations means the potential is greatest for THM formation in water plants and the distribution systems during this period.

The Grasse River and Glenmore Reservoir are good water supply systems to study. The organic matter in both supplies is derived from natural sources. The Glenmore Reservoir is a protected potable supply, and there are no significant upstream wastewater dischargers on the Grasse River. They are also contrasting systems. The Grasse River is highly colored due to humic substances leached from the upland watershed and bogs whereas a major source of organic matter for the Glenmore Reservoir is that produced within the reservoir from primary biological production—algal cells, algal by-products, and algal decomposition products.

The full-scale water plants at Canton and Oneida were each monitored on 16 dates between February 1980 and June 1982. The monitoring dates were selected to assess any effect of seasonal variation in water quality on plant performance. Raw water quality data are summarized in Table 8.3. These data show that the Grasse River contains higher amounts of color, NPTOC, THM precursors (TTHMFP), and higher UV (254 nm) absorbance values than the Glenmore Reservoir.

8.3.2 Description of Water Plants

The Canton treatment plant normally operates at a flow of 11.4 ML/day (3 MGD), and is a high-rate conventional-type plant. Treatment processes consist of coagulation-flocculation, sedimentation (tube settlers), and

TABLE 8.3
Raw Water Data for Canton and Oneida Water Plant Monitoring

	Canton (n = 16)		Oneida (n = 16)	
Raw Water Parameter	Mean	Range	Mean	Range
Temperature (°C)	8	0.5–23	11	3–21
pH	7.1	6.9–7.4	6.9	6.5–7.4
Turbidity (ntu)	2.1	1.2–3.2	1.4	0.54–3.5
True Color, Pt-Co	125	73–276	65	24–140
TOTL-UV (cm^{-1})	0.278	0.113–0.666	0.179	0.084–0.309
SOL-UV (cm^{-1})	0.279	0.137–0.640	0.165	0.085–0.317
NPTOC (mg/L)	6.1	2.75–14.7	4.7	2.0–10.65
TTHMFP (μg/L)	473	245–1108	320	152–597

TABLE 8.4
Treatment Conditions and Inst TTHM Data for the Canton and Oneida Plants

	Canton (Mean)	Oneida (Mean)
Alum dosage (mg/L)	42.5 (35–50)[a]	22.7 (12–44)
pH		
raw water	7.1 (6.9–7.4)	6.9 (6.5–7.4)
after settling	6.4 (5–6.9)	6.2 (5.5–6.6)
clearwell	6.5 (5.7–7.0)	7.5 (7.0–9.2)
Prechlorination (mg/L)		
rapid mix tank	1.1 (0–2.5)	See below[b]
top of filter		1.1 (0.7–2.9)
Postchlorination (mg/L)	1.7 (0–4)	3.4 (2.3–6.5)
Chlorine residual (mg/L)		
clearwell	1.1 (0.23–1.7)	2.5 (2.0–3.2)
Inst TTHM (μg/L)		
settled	10.2 (ND[c]–33.5)	9.2 (ND–87.5)
after filtration	10.2 (ND–43.6)	19.3 (ND–97.5)
clearwell	36.6 (ND–126.8)	47 (10.1–148.5)

[a] Range.
[b] Two occasions at 4.2 and 4.9 mg/L.
[c] ND, Not detectable.

filtration (mixed media filters). Summaries of treatment conditions for both plants are presented in Table 8.4. Alum coagulation under acidic pH conditions is practiced at Canton in treating the highly colored Grasse River. Prechlorination is normally practiced (rapid mix tank), but low chlorine dosages are used—average of 1.1 mg/L. The postchlorination dosage is also low, and is applied at a point between the filters and the clearwell.

The Oneida plant has a rated process capacity of 15.1 ML/day (4 MGD). It is a conventional plant using coagulation-flocculation, sedimentation (rectangular settling basins), and filtration (dual media filters). As indicated in Table 8.4, alum is used to treat this low turbidity supply. Currently, the chlorination practice includes a small dose on top of the filters followed by postchlorination. On two of the monitoring dates, the plant used high prechlorination doses because of reduced Fe and Mn in their raw water supply.

Samples were collected at several locations through the plants—raw, settled, filtered, and finished water (pumped water from clearwell to the distribution system). The analyses included temperature, pH, turbidity, apparent color, true color, total UV (254 nm) absorbance, soluble UV (254 nm) absorbance, NPTOC, instantaneous TTHM (Inst TTHM), TTHMFP, terminal TTHM (Term TTHM), and free residual Cl_2. For the raw waters, the 7-

day TTHMFPs (pH 7.5, 20°C) were used as the measure of raw water THM precursor concentration. Within the water plants, Term TTHM samples were buffered at pH 7.5 and spiked with chlorine to maintain a residual for 7 days—that is, Term TTHMs (7-day, pH 7.5, 20°C). THM precursor removal by treatment is the difference between the raw water 7-day TTHMFP and the 7-day Term TTHM at the sampling point chosen to evaluate treatment.

8.3.3 Illustrations of Plant Monitorings

The results of three plant monitorings are presented first to illustrate the effects of raw water THM precursor concentration, temperature, pH, and chlorination practice. Next the removals of NPTOC, THM precursors, and UV achieved by the plants are summarized and discussed. Finally, THM formation in the treatment plants is evaluated.

8.3.3.1 Canton Plant: Low TOC and Low TTHMFP

Plant monitoring results are shown in Figure 8.7 for winter water quality conditions. The raw water temperature (1°C) and concentrations of TTHMFP (255 μg/L), NPTOC (3.2 mg/L), and UV (0.151 cm^{-1}) were low. Process detention times are shown at the top of the figure. Note that this is a high-rate plant with a short hydraulic detention time—only 60 min ahead of the clearwell. Overall plant performance for removals of organic matter and THM precursors is based on raw water data and filtered water data. Sampling after a specific filter is preferred to sampling after the clearwell because the water quality in the clearwell reflects a composite of several filters. Sampling ahead of the clearwell permits sampling from a common train of flocculation and sedimentation tanks leading to designated filters.

The plant performs well with good removals of TOC and THM precursors: 69% for Term TTHM (i.e., THM precursors), 60% for NPTOC, and 67% for UV absorbance. The turbidity and NPTOC data show that the filters do most of the work under cold water conditions. Removals prior to filtration are poor. The effect of water temperature on performance will be discussed later. THM formation through the plant as indicated by the Inst TTHM data is low, only 25 μg/L in the water following the clearwell. Several factors contribute to this, including the low raw water precursor concentration, the chlorination practice (low prechlorination and postchlorination doses; no free chlorine residual measured ahead of the clearwell), and pH conditions through the plant (pH 6.5–7.3), but the single most important factor is the low water temperature, which slows the rate of THM formation.

8.3.3.2 Canton Plant: High TOC and High TTHMFP

Figure 8.8 illustrates monitoring results under early summer water quality conditions when the concentrations of TTHMFP and TOC are relatively

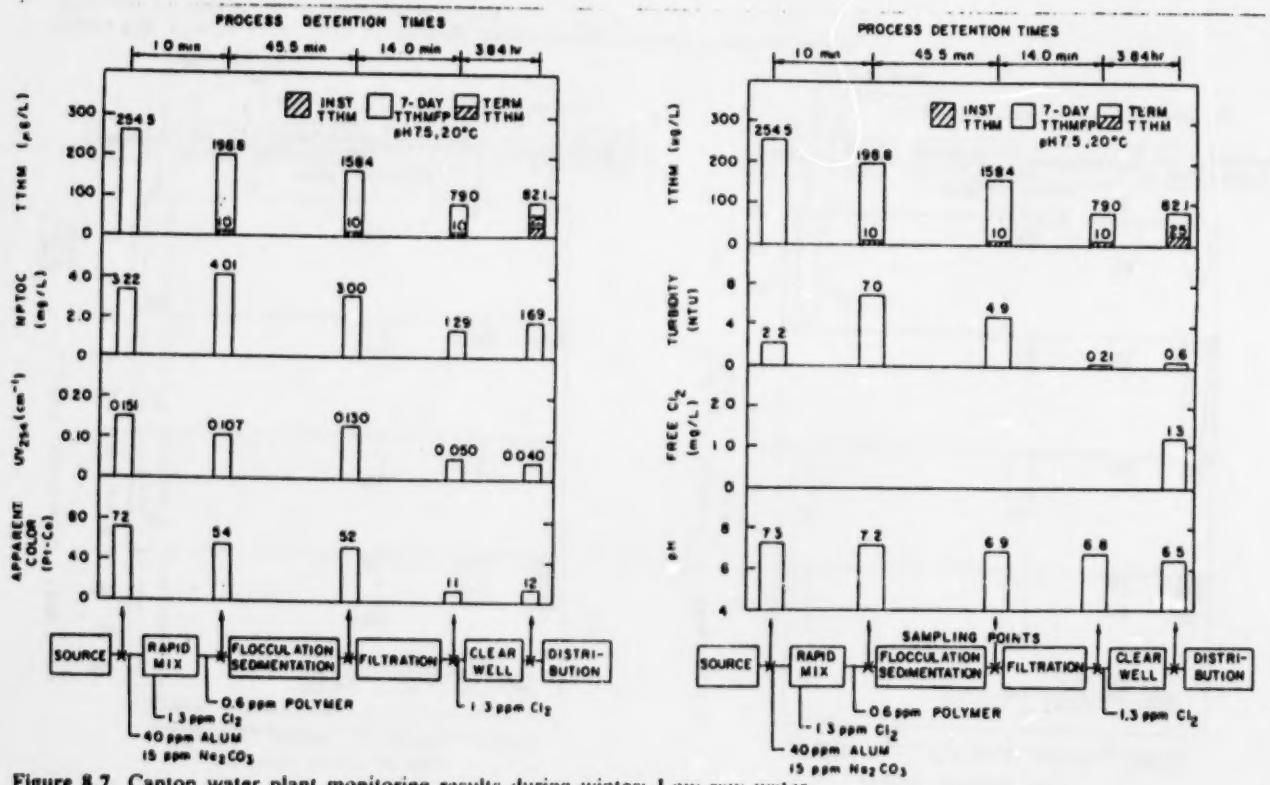

Figure 8.7. Canton water plant monitoring results during winter: Low raw water TOC and TTHMFP, water temperature at 1–2.5°C.

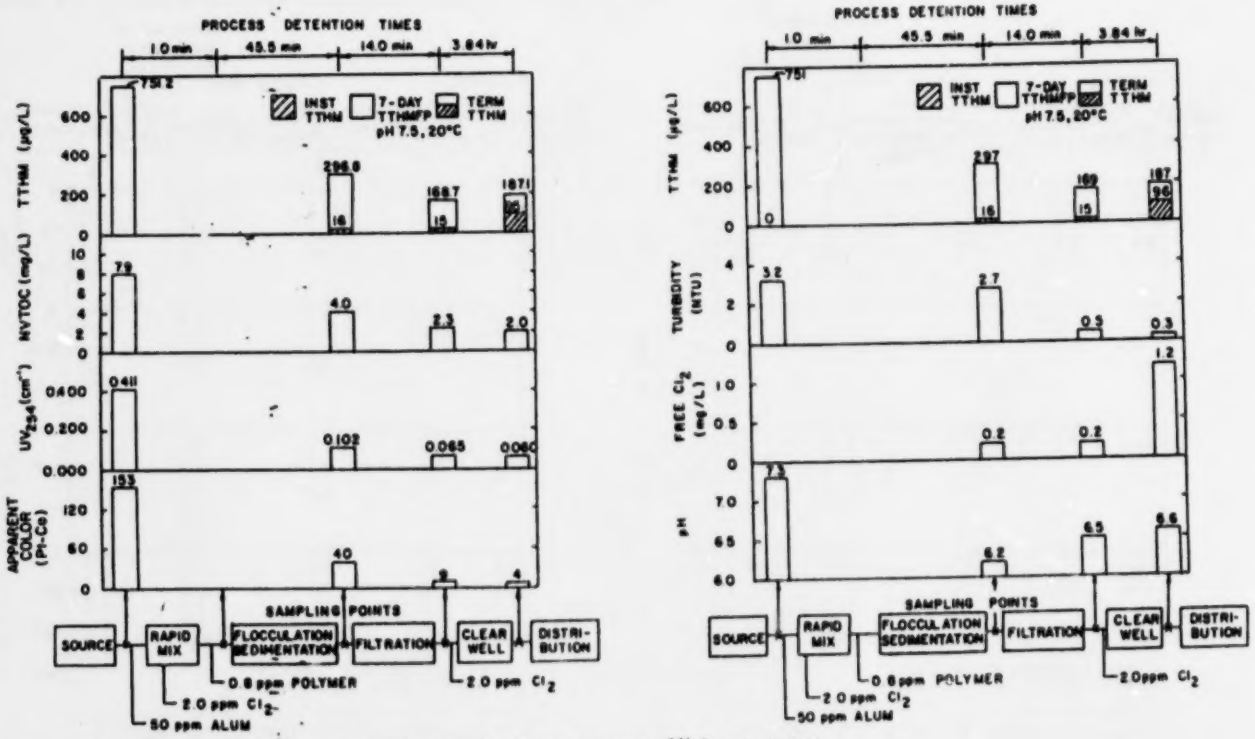

Figure 8.8. Canton water plant monitoring results during summer: High raw water TOC and TTHMFP, water temperature at 19°C.

high and the water temperature is 19°C. Again overall plant performance for removals of Term TTHM, NPTOC, and UV is good. In contrast to the prior case, substantial removals are accomplished prior to filtration—that is, by coagulation-flocculation and sedimentation.

THM formation through the plant prior to the clearwell is low—Inst TTHM of 15 μg/L after the filter—considering the high raw water precursor concentration. This is attributed to the pH conditions of treatment (less than pH 6.5 after prechlorination), the short detention period, and the prechlorination practice. The raw water contains a high concentration of TOC and would have a high chlorine demand, but a relatively low prechlorination dose of 2 mg/L was applied. A free chlorine residual of 0.2 mg/L was measured through the plant, but this free chlorine concentration is too low to drive the THM formation reaction and, therefore, limits THM formation. An Inst TTHM concentration of 95 μg/L is measured after the clearwell due to the postchlorination dose of 2 mg/L (free residual of 1.2 mg/L) and the nearly 4-h detention period in the clearwell.

8.3.3.3 Oneida Plant: Effect of Preoxidant

During the summer stratification period for the Glenmore Reservoir, reduced Fe and Mn present in the raw water require oxidation and removal by the Oneida treatment plant. Monitoring results presented in Figure 8.9 contrast the use of two preoxidants, chlorine and potassium permanganate ($KMnO_4$). The plant is a conventional one with long rectangular sedimentation basins. Process detention times listed at the top of the figure show a long hydraulic detention period of 6 h in the plant prior to the clearwell.

Figure 8.9*a* shows that when chlorine is used as a preoxidant, removal of THM precursors is poor and THM formation is high. The Inst TTHM concentration of 134 μg/L after the clearwell exceeds the MCL for TTHMs of 0.10 mg/L. Additional THM formation occurs in the distribution system. Two samples collected from the distribution system had concentrations of 211 and 221 μg/L. The THM formation problem is caused largely by using a high prechlorination dose of 4.2 mg/L in the rapid mix basin. The need for a high postchlorination dose at a high pH (pH 8.6) also contributes to the high THMs. The postchlorination practice of relatively high chlorine addition is due to a 20-mile transmission main to the city in which a free chlorine residual must be maintained. The high pH was due to their corrosion control practice used during this monitoring period. Their corrosion control practice was later changed.

The following summer Oneida switched to potassium permanganate as a preoxidant. Figure 8.9*b* shows the results for a date in which the raw water THM precursor concentration was its highest over a 30-month period. The benefit of using potassium permanganate is shown by the relatively low THM formation through the plant—60 μg/L Inst TTHM after the clearwell. The plant also benefited from a change in corrosion control practice to

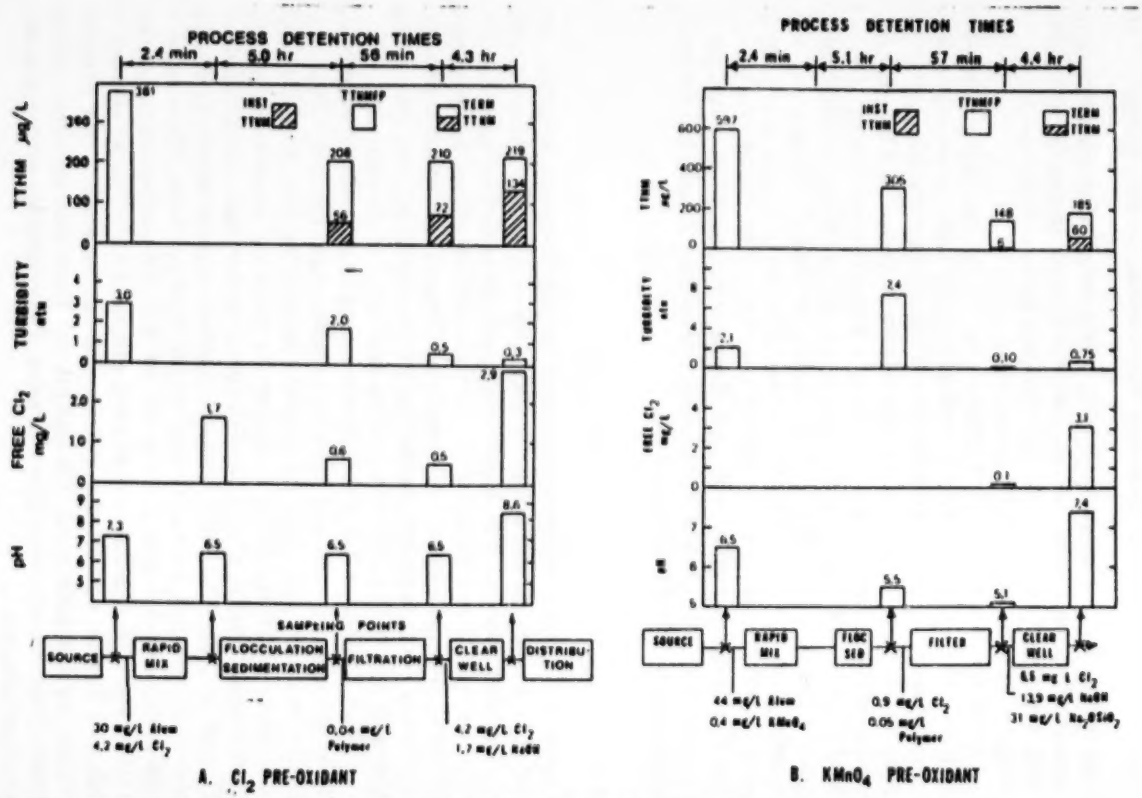

Figure 8.9. Oneida water plant monitoring results: Effect of preoxidants prechlorination (*a*) and potassium permanganate (*b*).

sodium silicate, which allows finished water pH at a full pH unit lower than prior practice. Elimination of prechlorination permitted good plant performance for removing THM precursors, 75% on this date.

8.3.4 Discussion of Performance

8.3.4.1 Summary of Removals

The Grasse River and Glenmore Reservoir water supplies are different in terms of type, origin of organic matter, and concentrations of organic matter and THM precursors. In spite of these differences the data in Table 8.5 show that both water plants achieve excellent and similar removals of NPTOC, UV (254 nm), and Term TTHMs (THM precursors).

The excellent performance of the Canton plant in both removing THM precursors and controlling THM formation through the water plant is due to the effectiveness of the coagulation process, pH conditions during treatment, chlorination practice, the short hydraulic detention time of the plant, and the relatively low water temperatures. The Canton plant uses alum coagulation with the addition of a nonionic polymer to aid floc formation. Normally coagulation is practiced at pH 5.5–6 (rapid mix tank) which is optimum according to the principles presented in Section 8.2. In spite of the high THM precursor concentrations in the Grasse River, the average Inst TTHM concentration of the finished water was only 37 μg/L (see Table 8.4). Although prechlorination is practiced, the dosages are low at 1–2 mg/L. The plant has tube settlers so that the total hydraulic detention time through the plant (excluding the clearwell) is approximately 1 h. The prechlorination practice and the short hydraulic detention time allow removal of THM precursors before large concentrations of THMs are formed.

The Oneida plant also achieves excellent removals of NPTOC and THM precursors. It also practices alum coagulation at pH conditions near op-

TABLE 8.5
Performance Summaries for the Canton and Oneida Water Plants

	Mean Percent Removals[a]	
Parameter	Canton (n = 16)	Oneida (n = 12)
NPTOC	69 (8)[b]	71 (14)
Total UV (254 nm)	80 (7)	82 (4)
Soluble UV (254 nm)	84 (6)	81 (7)
Term TTHM[c]	72 (5)	68 (7)

[a] Excludes performance data for Oneida during the first year when chlorine was used at the plant as a preoxidant.
[b] Standard deviation.
[c] 7-day, free Cl_2 present, pH 7.5, 20°C.

timum. The detention time through the Oneida plant (excluding the clearwell) is approximately 6 h. Seasonal problems with Fe and Mn in the Glenmore Reservoir require use of a preoxidant. The type and dosage of preoxidant has a significant effect on Inst TTHM concentrations in the finished water. The data in Table 8.6 show that when chlorine was used as a preoxidant, the Inst TTHM concentration exceeded the MCL of 0.10 mg/L. The plant substituted potassium permanganate for chlorine as a preoxidant, and they changed their corrosion control practice so that the treated water has a pH of 7–7.5. These changes have controlled THM formation in the plant, as shown by the data in Tables 8.4 and 8.6. Chlorine is still added, but at relatively low doses to the top of the filters and to the clearwell.

8.3.4.2 Effect of Temperature

Temperature effects on removals of THM precursors and on Inst TTHMs are discussed using data from Canton. The data in Table 8.7 show that overall treatment plant efficiences for removal of NPTOC, UV (254 nm), and THM precursors are not significantly affected by temperature; however, water temperature does affect where in the treatment plant the removals take place. For cold water conditions, the organic matter is coagulated, but settling of the floc is poor so that a large portion of the removal takes place in the filters during the winter months. Similar results were observed for the Oneida plant.

Water temperature also influences the Inst TTHM concentration of the treated water. The data in Table 8.8 demonstrate that at the higher water temperatures, the mean Inst TTHM concentration and variation are much higher than at colder water temperature conditions.

8.3.5 UV as a Surrogate Parameter

8.3.5.1 Plant Monitoring of TOC and THM Precursors

UV absorbance at 254 nm is explored as a surrogate parameter for NPTOC and THM precursors (7-day TTHMFP, pH 7.5, 20°C). Linear least-squares regression analysis was used to develop predictive equations from the data. Two sampling locations were used for the data base: raw water and filtered water (filter effluent).

Figure 8.10 illustrates the correlation between NPTOC and UV for the Canton water plant. A summary of the predictive equations for both the Canton and Oneida water plants is given in Table 8.9. The statistical measures in the table indicate how much of the variation (r^2) in the dependent variable is explained by the predictive equation and the significance of the regression (α). These statistical measures show that UV is an excellent parameter for estimating TOC and THM precursors. The predictive equations can be used to estimate raw water and treated water quality, and

TABLE 8.6
Effect of Preoxidant Practice on THM Formation in the Oneida Water Plant

Preoxidant	Dosage range (mg/L)	Number of monitorings	Clearwell Inst TTHMs (μg/L)
Cl_2	4.2–4.9	2	141
$KMnO_4$[a]	0.12–0.7	6	35
None[a]	0	6	20

[a] 0.7–1.1 mg/L Cl_2 on top of filters.

TABLE 8.7
Effect of Water Temperature on Performance at the Canton Water Plant

	Mean Percent Removals			
	Temp. 0.5–5°C (n = 9)		Temp. 9–23°C (n = 7)	
	Sed.[a]	Filt.[b]	Sed.[a]	Filt.[b]
NPTOC	25 (14)[c]	65 (8)	43 (15)	73 (4)
Total UV (254 nm)	44 (17)	79 (7)	67 (8)	81 (7)
Term TTHM[d]	42 (9)	70 (5)	53 (8)	74 (4)

[a] Cumulative removal by coagulation-flocculation and sedimentation.
[b] Cumulative removal by coagulation-flocculation, sedimentation, and filtration.
[c] Standard deviation.
[d] 7-day, free Cl_2 present, pH 7.5, 20°C.

TABLE 8.8
Effects of Temperature on Clearwell Water Inst TTHMs at the Canton Water Plant

Case	n	Inst. TTHM (μg/L)
All data	16	37 (33)[a]
Temperature		
0.5–5°C	9	23 (14)
9–23°C	7	54 (44)

[a] Standard deviation.

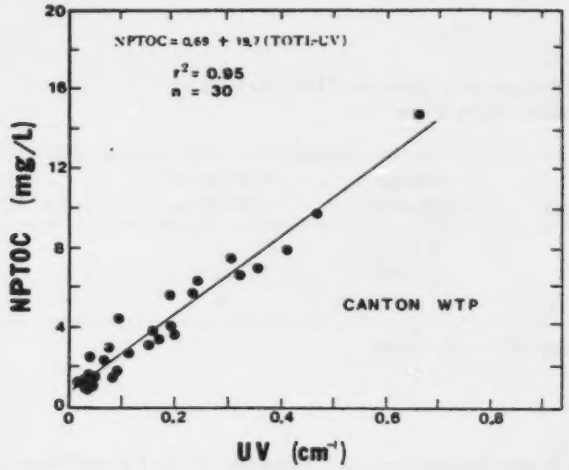

Figure 8.10. Correlation between NPTOC and TOTL-UV (254 nm) for raw and finished waters for the Canton water plant.

therefore monitor overall plant performance. UV absorbance has certain attributes that make it a good surrogate parameter for water plant monitoring and operational control. It can be measured easily, rapidly, and inexpensively. The equipment (UV spectrophotometer) could be installed on-line providing real time, continuous measurements.

The selection of sampling locations and sample handling procedures are important factors when considering UV as a surrogate parameter (19). UV absorbance measurements are affected by pH, turbidity, and oxidants. Sample handling procedures should consider pH adjustment of all samples prior

TABLE 8.9
UV Predictive Equations for NPTOC and TTHMFP for the Canton and Oneida Water Plants

Equation	r^2	α	n
Canton[a]			
NPTOC = 19.7 (TOTL-UV) + 0.69	0.95	0.0001	30
TTHMFP = 1629.3 (TOTL-UV) + 37.8	0.97	0.0001	31
Oneida[b]			
NPTOC = 25.0 (TOTL-UV) + 0.40	0.86	0.0001	29
TTHMFP = 1578.2 (TOTL-UV) + 42.4	0.94	0.0001	31

[a] *Range in Data:* TOTL-UV, 0.016–0.666 cm^{-1}; NPTOC, 0.80–14.7 mg/L; TTHMFP, 69–1108 μg/L.
[b] *Range in Data:* TOTL-UV, 0–0.309 cm^{-1}; NPTOC, 0.21–10.6 mg/L; TTHMFP, 50–597 μg/L.

to measurement of UV to normalize the data to a standard pH value. Floc or turbidity in samples may interfere with the light absorbance measurements, requiring filtering of samples. Strong oxidant addition in water plants can be a problem because of a reduction in UV absorbance due to an alteration of the structure of the organic molecules without any real reduction in TOC or THM precursors. This may require selecting sampling locations ahead of points of strong oxidant addition, otherwise poor correlations may result.

8.3.5.2 Predicting Inst TTHMs

UV absorbance as a surrogate for THM precursors as developed above does not tell you directly whether you meet the maximum contaminant level (MCL) for THMs in drinking water. The MCL is based not on the concentration of THM precursors remaining, but on the concentration of THMs formed and existing in the treated water at the time of sampling—that is, the Inst TTHM concentration. Development of a general predictive equation for the Inst TTHM concentration of water leaving a treatment plant is difficult. Theory dictates that THM formation through a treatment plant shall depend on raw water quality variables, water plant operational variables, and plant design variables. Raw water quality variables include THM precursor concentration, temperature, and for some waters, the bromide concentration. Plant operating variables include pH during treatment, chlorination practice (locations and dosages), and the efficiency of the removal of THM precursors. Plant design variables are hydraulic detention time through the plant, the processes used to accomplish removals of THM precursors, and where removal takes place in the plant relative to chlorine application.

Correlations were developed on an individual basis for the Canton and Oneida plants. Therefore, plant design variables are fixed, and implicitly part of the developed predictive equations. Linear correlations between the Inst TTHMs of the finished water (water leaving the clearwell) and single independent variables produced the following results. The Inst TTHM concentration was highly correlated with total chlorine consumption for the Canton water plant and prechlorine consumption for Oneida (19). Total chlorine consumption is the sum of all chlorine dosages less the free chlorine residual of the finished water leaving the clearwell. For Oneida prechlorine consumption is the difference between the total chlorine dose applied to both the rapid mix tank and to the filters less the free chlorine residual following filtration.

Linear multiple regression analysis was used to obtain the predictive equations presented in Table 8.10. The correlations are good, significant, and satisfy theoretical criteria. Inst TTHMs through the plant depend on raw water quality (THM precursor concentration) and plant operation (pH and chlorine consumption). The precursor concentration is measured by a surrogate parameter, UV (254 nm). Raw water temperature is included in the Canton predictive equation, but is not needed for Oneida. Finished water pH

TABLE 8.10
Multiple Regression Predictive Equations for Inst TTHMs in Finished Drinking Waters

Equation[a]	r^2	α	n
Canton			
Inst TTHM = − 278.0 + 11.1(A) + 47.1(B) + 12.8(C) + 2.71(D)	0.88	0.001	16
Oneida			
Inst TTHM = − 111.4 + 11.8(B) + 163.6(C) + 30.1(E)	0.96	0.0001	16

[a] A = total chlorine consumption; B = finished water pH; C = raw water UV (254 nm); D = raw water temperature; E = prechlorination consumption.

was used to account for pH effects on THM formation rather than other sampling points because a large fraction of the hydraulic detention time for both plants occurs in the clearwell. These predictive equations are good for Canton and Oneida only, because the plant design and operational variables (removals of precursors, points of chlorination, and detention times) for these plants are implicitly included in their development. They do illustrate, however, that predictive relationships can be obtained for water treatment plants. The framework used here could be used by water utilities to develop their own predictive equations. Predictive equations could provide water plant personnel with an estimate of Inst TTHMs in their finished water.

8.4 DIRECT FILTRATION

It was pointed out earlier that direct filtration facilities for potable water supplies in North America have been designed primarily on the basis of turbidity removal. There is little published information on the treatment of colored waters by direct filtration, particularly with cationic polyelectrolytes as the sole coagulants (23–25,27,28). This section addresses direct filtration with regard to traditional measures of performance (turbidity, color, and head loss development) and also to removals of NPTOC, THM precursors (TTHMFPs), and UV (254 nm) absorbance using cationic polymers and alum as the primary coagulants. Other points covered are the selection of cationic polymer dosages, the performance of small-scale versus large-scale pilot plants, in-line direct filtration versus direct filtration with flocculation, and the use of UV absorbance as a surrogate parameter for monitoring direct filtration performance.

8.4.1 Pilot Plant Studies

The two model water supplies described in Section 8.3.1 were used in the direct filtration studies—the Grasse River, a highly colored supply, and the Glenmore Reservoir, a low turbidity, protected upland water source.

Small-scale studies were conducted using Plexiglass* columns of 4.45 cm i.d. Dual media filters were used with an anthracite depth of 38.1 cm (ES (effective size) of 1.0–1.2 mm) over 15.2 cm of sand (ES of 0.45–0.55 mm). The large-scale studies employed a Waterboy* pilot plant with a filter area of 0.372 m^2 (4 ft^2), and was operated at flows of 0.5–1.51 L/s (8–24 gpm). A dual media filter was used with 50.8 cm of anthracite (ES of 1.0–1.2 mm) over 25.4 cm of sand (ES of 0.45–0.55 mm). A schematic of the large-scale pilot plant is presented in Figure 8.11.

The pilot plants were operated, as needed, over a 2-year period to evaluate seasonal changes in raw water quality on performance. THM precursor removal was calculated as the difference between the 7-day TTHMFPs (pH 7.5, 20°C) of the raw and filtered waters. The pilot plant studies were also designed to evaluate the effects of chemical treatment variables (pH, various cationic polymers as sole coagulants, and alum) and physical variables (filtration rate, in-line direct filtration versus direct filtration with flocculation, and water temperature) on filtration performance.

8.4.2 Cationic Polymer Dosage Selection

Jar tests can be used to select cationic polymer dosages for direct filtration (23,29). Testing of jar test data against direct filtration data is shown by the

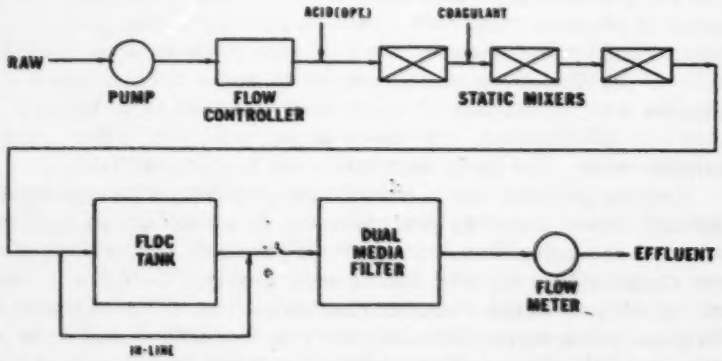

Figure 8.11. Schematic of direct filtration pilot plant.

* Mention of trade names or commercial products in this chapter does not constitute endorsement or recommendation for use.

results in Figure 8.12. The jar test results plotted in the top figure show a sharp drop in true color at cationic polymer dosages of 2–4 mg/L; above 4 mg/L, little change occurs in the true color readings. These results indicate that the required polymer dose for coagulation is 4 mg/L. The bottom figure shows direct filtration results where the polymer dose was varied during the course of the experiment. Best results were obtained at 4 mg/L, as the jar tests predicted. Underdosing and overdosing occur in direct filtration and can be predicted from the jar test data.

For colored waters such as the Grasse River, the cationic polymer dose required for coagulation depends on the raw water concentration of organic matter. This is illustrated by the data in Figure 8.13 which shows a correlation between the polymer dose (Magnifloc 573C) and total UV (254 nm). UV absorbance is used here as a surrogate for TOC. These results are highly significant and practical. The predictive equation developed in this study is specific to the Grasse River, but the principle is generally applicable. In practice, a water utility could make on-line spectrophotometric UV measurements of the raw water quality. From a predictive equation relating polymer dose to raw water UV (254 nm), the utility could then estimate the polymer dosage needed for coagulation.

8.4.3 Performance with Cationic Polymers

8.4.3.1 Grasse River

Figure 8.14 shows results for two pilot plant experiments conducted in the summer when the color and TOC concentration are high. Consequently, polymer coagulant doses are high. The experiments compare in-line direct filtration with direct filtration preceeded by flocculation at a filtration rate of 4.88 m/h and without pH adjustment of the raw water. Excellent filter performance is obtained using only a cationic polymer to treat a highly colored water. Furthermore, there is little difference in the apparent color and turbidity of the filtered water when treated by in-line direct filtration or direct filtration with flocculation. A major difference does exist, however, in the head loss development, with much greater head loss in the in-line direct filtration mode. This latter observation will be discussed later.

Cationic polymers can be used as sole coagulants in the treatment of low turbidity, humic waters by direct filtration. Raw water quality with apparent color values ranging from 50 to 200 Pt-Co color units and turbidity of 1–6 ntu was treated effectively with filtered water quality of 5–10 Pt-Co color units and turbidity of 0.2 ntu. Filtration rate (varied from 4.88 to 14.6 m/h), type of filtration (in-line versus direct filtration with flocculation), and water temperature had little effect on filter performance based on removals of turbidity, color, and organic matter. The effect of pH on removals of organic matter is discussed later.

Cationic polymer dosages for direct filtration vary seasonally with

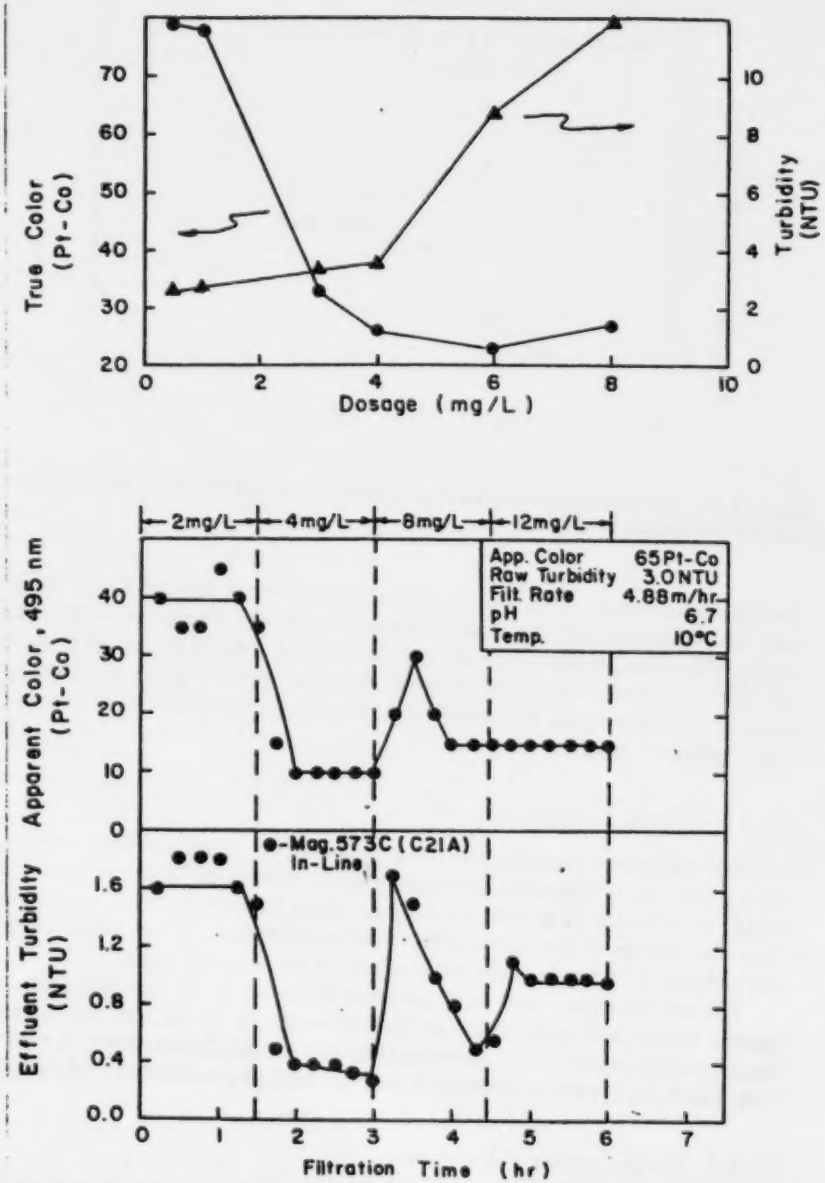

Figure 8.12. Testing of jar test predictions with direct filtration pilot plant data for the Grasse River. (Top): Jar test data using a cationic polymer. (Bottom): Direct filtration results for varying dosages of cationic polymer during the filter run. Note polymer feed pump off briefly after 3 hours.

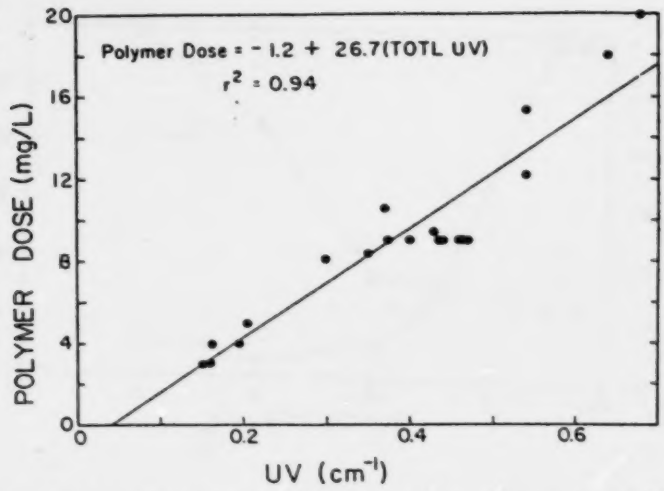

Figure 8.13. Correlation between cationic polymer dose and raw water total UV (254 nm) for the Grasse River.

changes in the concentrations of organic matter in the Grasse River. Polymer dose requirements are relatively low (3–4 mg/L) during the winter and spring when the raw water quality is good (see Fig. 8.6). In the summer when the TOC and color are high, polymer dosages of 9–12 mg/L are needed. Natural waters of lower TOC and color than the Grasse River would require lower polymer doses.

8.4.3.2 Glenmore Reservoir

Cationic polymers can also be used successfully to treat a low turbidity supply like the Glenmore Reservoir. This is illustrated by the results presented in Figure 8.15 in which a polymer dose of only 2.5 mg/L is needed. Over the course of the study, filtered water turbidities of less than 0.3 ntu and color of 5-15 Pt-Co units were achieved on a regular basis.

Polymer dosages vary with seasonal changes in the concentration of organic matter and particulates in the raw water. However, the variation in dosage requirements is less extreme than that for the Grasse River; it varied from 2 to 6 mg/L with an estimated average annual concentration of 4 mg/L.

8.4.3.3 In-Line versus Flocculation

It was stated earlier that the removals of organic matter, filtered water turbidity, and color did not differ between in-line direct filtration and direct filtration with a flocculation period provided by a flocculation basin. For the

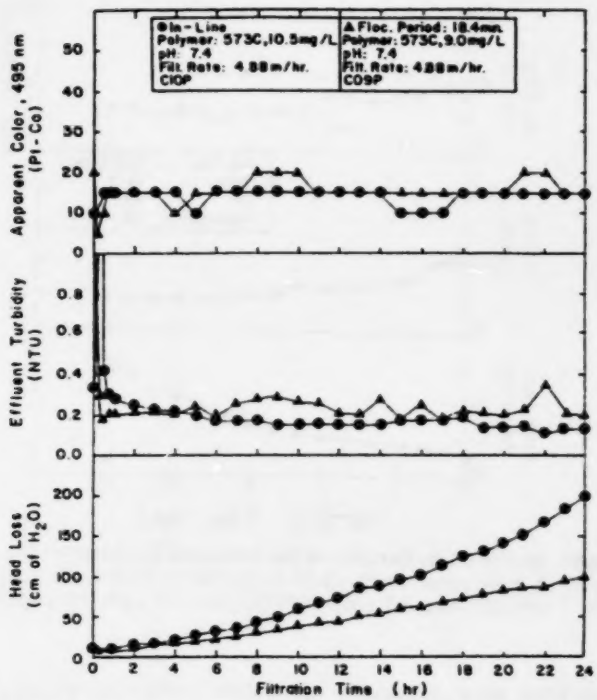

Figure 8.14. Direct filtration of the Grasse River with a cationic polymer: In-line treatment versus direct filtration with a flocculation period prior to filtration. Raw water quality: 2.5 ntu turbidity, 108–115 Pt-Co units apparent color, 0.37–0.40 cm^{-1} UV (254 nm), 7.3–8 mg/L NPTOC, and 657–674 μg/L TTHMFP.

Grasse River in particular, there was significantly less head loss development when treating the same water by direct filtration with flocculation compared to in-line direct filtration (see Fig. 8.14). These results are significant and have important design ramifications.

In the treatment of a water like the Grasse River, direct filtration with flocculation will give longer filter runs. This is explained by considering that water with large amounts of humic matter contains high concentrations of submicron particles (the humic particles). By providing a flocculation period through the use of a flocculation basin or otherwise, the humic particles after coagulant (cationic polymer) addition can aggregate to larger sizes. This causes a reduction in the number and surface area of the floc particles retained in the filter compared to in-line filtration. The larger particles through flocculation produce less head loss development and longer filter runs.

A flocculation period is recommended in direct filtration since it will

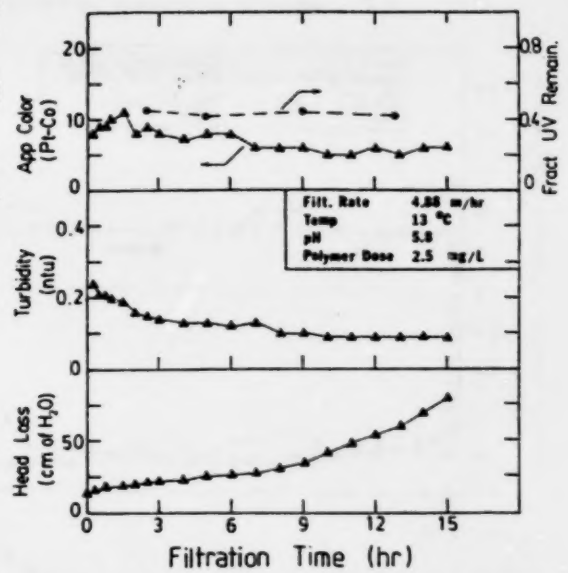

Figure 8.15. In-line direct filtration of the Glenmore Reservoir with a cationic polymer at pH 5.8. Raw water quality: 0.74 ntu turbidity, 38 Pt-Co units apparent color, 0.105 cm^{-1} UV (254 nm), 3.2 mg/L NPTOC, and 175 µg/L TTHMFP.

lengthen filter runs, especially for waters containing submicron particles (humics, viruses, asbestos, etc.). The flocculation tank also provides the water plant operator with time to adjust chemical (coagulant) dosages for direct filtration when changes in raw water quality occur.

8.4.4 Alum

Alum is frequently used in direct filtration practice either with or without a polymeric filter aid. Its use is generally limited to high-quality raw waters of low turbidity and low TOC to avoid high alum dosages.

Alum can be quite effective in treating a colored water by direct filtration, as illustrated by the results in Figure 8.16 for the Grasse River. Excellent performance is noted in terms of filtered water turbidity and color. However, the alum dose is relatively high at 14 mg/L, even at pH 5.5, causing high head loss development and a short filter run. This filter experiment was conducted during the winter when the TOC concentration of the Grasse River was relatively low, 4.1 mg/L.

In general, alum dosages are high for the Grasse River due to the high color and high TOC. Under summer water quality conditions, alum dosages at pH 5.5 can exceed 20 mg/L. Alum works well in treating the Glenmore Reservoir by direct filtration (20). To produce water of low turbidity with

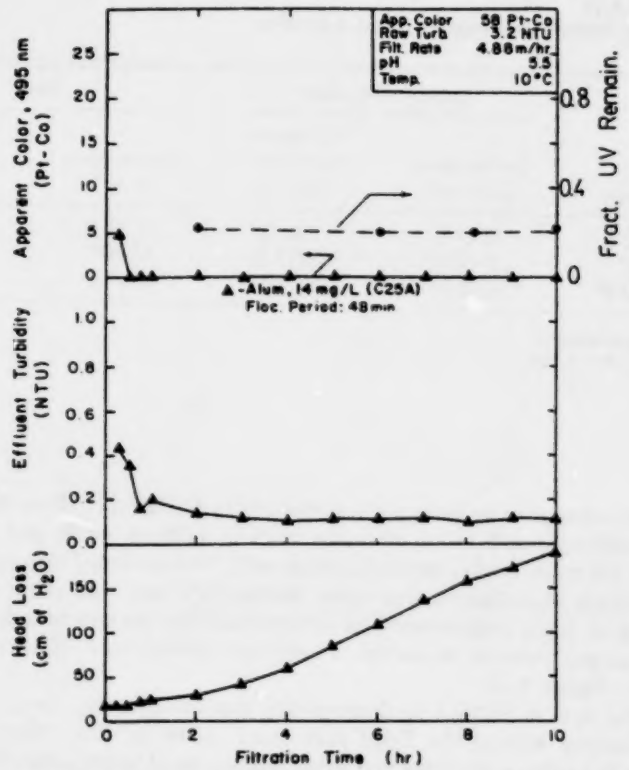

Figure 8.16. Direct filtration with flocculation of the Grasse River using alum at pH 5.5. Raw water quality: 3.2 ntu turbidity, 58 Pt-Co units apparent color, 0.168 cm^{-1} UV (254 nm), 4.1 mg/L NPTOC, and 252 μg/L TTHMFP.

low concentrations of TOC and THM precursors, alum dosages of about 10 mg/L at pH 5.5–6 are necessary. Even under well-controlled conditions of pH and applied alum dosages, direct filtration is difficult since precipitation of aluminum hydroxide can occur. Parallel reactions described in Section 8.2.3.3 and Figure 8.4 illustrate the problem. Treatment above pH 6 or treating waters with TOC above 4–5 mg/L probably results in the precipitation of aluminum hydroxide. The additional suspended solids applied to the filters would cause short filter runs.

8.4.5 Removals of NPTOC and THM Precursors

8.4.5.1 General

Average percent removals for UV (254 nm), NPTOC, and THM precursors (TTHMFP) achieved by direct filtration, using either a cationic polymer as

TABLE 8.11
Average Percent Removals by Direct Filtration

Percent Removals	Cationic Polymer		Alum	
	Grasse River (n = 18)	Glenmore Reservoir (n = 8)	Grasse River (n = 7)	Glenmore Reservoir (n = 9)
Total UV	58 (6.2)	51 (8.7)[a]	76 (4.3)	71 (7.8)
NPTOC	37 (6.0)	39 (12.2)	57 (9.7)	56 (17.6)
TTHMFP[b]	42 (8.8)	41 (5.1)	59 (8.2)	59 (9.1)

[a] Standard deviation.
[b] 7-day, pH 7.5, 20°C.

the sole coagulant or alum are summarized in Table 8.11. These data are for pH conditions of 5.2–7.5, filtration rates of 4.88–14.6 m/h, and for in-line direct filtration versus direct filtration with flocculation. Filtration rate, in-line versus flocculation, and water temperature had little effect on performance. A slight improvement in removal efficiencies can be achieved with cationic polymers by operating at lower pH conditions as illustrated by the data in Figure 8.17.

The data in Table 8.11 demonstrate that cationic polymers remove approximately 40% of the THM precursors. Alum in direct filtration yields higher removals with THM precursor reductions of approximately 60%. It is interesting that the removal efficiencies of each coagulant do not depend on the water source. The Grasse River and Glenmore Reservoir are different type waters, yet the removal efficiencies are approximately the same. A discussion of the applicability of the two coagulants in conventional water treatment and direct filtration is presented in Section 8.5.

8.4.5.2 UV as a Surrogate Parameter

Edzwald et al. (19) have shown that UV (254 nm) absorbance is an excellent surrogate parameter for monitoring direct filtration pilot plants. For pilot plant studies using Grasse River water, UV explained 90% of the variation of the TTHMFP data and 86% of the variation of NPTOC. For Glenmore Reservoir pilot plant data, it explained 89% of the variation of TTHMFP and 72% of the variation of NPTOC. An advantage of using UV to monitor NPTOC and TTHMFP in pilot plant studies is that it can provide an instantaneous assessment of performance due to any raw water quality changes or changes in pilot plant treatment or operation.

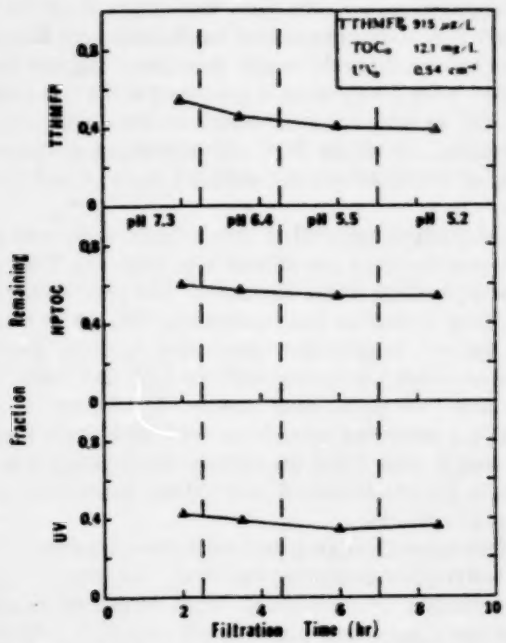

Figure 8.17. Direct filtration of the Grasse River with a cationic polymer: Effect of pH on removals of TTHMFP, NPTOC, and UV (254 nm).

8.4.5.3 Performance of Small-Scale and Large-Scale Pilot Plants

Pilot plant studies of direct filtration were conducted on both a small-scale (filter columns of 4.45 cm i d.) and a large-scale (filter bed surface of 0.372 m^2). An important finding was that the small-scale pilot plant gave similar results to the large-scale plant in evaluating various coagulants and coagulant dosages, filtered water turbidity and color, and removals of organic matter and THM precursors. This was true for both the Grasse River and the Glenmore Reservoir. This is important since small-scale pilot plants are cheaper to construct and operate. Large-scale pilot plants are necessary, however, to evaluate length of filter runs, head loss development, and backwashing.

8.5 SUMMARY

Alum coagulation is an effective treatment process for the removal of TOC and THM precursors from water supplies containing naturally occurring

organic matter, especially humic materials. The results of field studies on two water supplies support the view that optimum pH for alum coagulation occurs at pH 5–6. Two coagulation mechanisms are described in the chapter. The mechanism depends on pH, alum dose, and raw water TOC concentration. When alum coagulation is practiced at pH 5–6 on waters containing 4–5 mg/L TOC or less, the mechanism involves precipitation of aluminum-humate particles. At higher TOC concentrations or higher pH conditions, the removal of dissolved organic matter occurs by adsorption on aluminum hydroxide.

The field studies reported in this chapter show that conventional-type water treatment facilities are effective in removing TOC and THM precursors and in controlling THM formation. The two water supplies examined achieved similar removals (approximately 70% for TOC and THM precursors); yet, the two supplies are contrasting systems. The Grasse River is a highly colored water supply in which the TOC and 7-day TTHMFP reached 14.7 mg/L and 1108 μg/L, respectively. The Glenmore Reservoir, on the other hand, is a protected upland reservoir with much lower concentrations of organic matter and THM precursors. Both plants use alum coagulation near optimum pH conditions. It is noted that both water supplies are low in alkalinity and hardness.

THM formation through a treatment plant depends on raw water quality variables, water plant operating variables, and plant design variables. Both plants are effective in controlling THM formation because of the effectiveness of the coagulation process, pH conditions during treatment, and their chlorination practice. Where prechlorination is practiced, low doses are used. Seasonal problems with Fe and Mn in the Glenmore Reservoir require use of a preoxidant. Substitution of potassium permanganate for chlorine significantly reduced THM formation.

Direct filtration with cationic polymers as the sole coagulant is a feasible treatment process. Waters containing high color can be treated yielding excellent filtered water quality in terms of turbidity and color. Approximately 40% of the TOC and THM precursors are removed by direct filtration with cationic polymers. This process is not as effective as direct filtration with alum or conventional water treatment employing alum in the removal of TOC and THM precursors. In practice, the performance of direct filtration must be evaluated through pilot plant studies. The following guidelines are proposed, however, regarding direct filtration with cationic polymers as the sole coagulant. Direct filtration is a potentially feasible method of treatment for waters of low to moderate TOC and TTHMFP levels, say mean annual TOC of 4–5 mg/L and TTHMFP of 350–400 μg/L. For waters with higher concentrations, conventional water treatment is preferred for removals of TOC and THM precursors and control of THM formation.

UV (254 nm) absorbance is a good surrogate parameter for TOC and THM precursors. It can be used to monitor their removal in laboratory studies, pilot plants, and full-scale treatment plants.

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